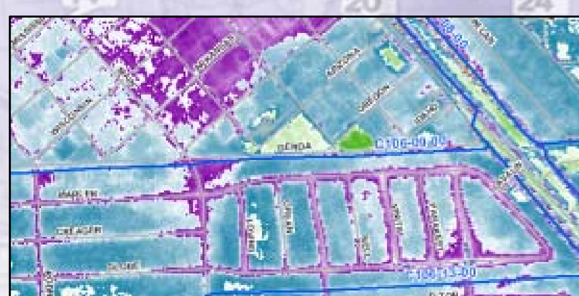
City of Houston, Texas
Department of Public Works and Engineering
Technical Paper No. 101
(TP-101)

Simplified 100-year Event Analyses of Storm Sewers and Resultant Water Surface Elevations for Improvement Projects in the City of Houston, Harris County, Texas Region



SWMP
Houston Storm Water Management Program

December 22, 2004

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Abstract

This Technical Paper No. 101 (TP-101) serves as a practical guide to the simplified design process that may be employed for storm sewers and overland flow considerations in accordance with Chapter 9 of the City of Houston Infrastructure Design Manual[1]. As required by the Manual, the 100-year hydraulic grade line of a storm sewer serving a roadway section is to remain at or below the natural ground elevations of the roadway rights-of-way as a provision to provide an increased flood protection level-of-service. The methods described within this technical paper are intended to serve as guidelines to aid a designer in adhering to this requirement and in the consideration of overland flow within public and private projects without the utilization of complex computer simulations or other more arduous computational procedures. Open channels and roadside ditches are not specifically covered in this paper; however, the theoretical application is similar.

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[1] City of Houston Department of Public Works and Engineering Infrastructure Design Manual, Revision 3, October 1, 2004.

1.0 Basic Applications

Due to the naturally recurring storm events in the Houston, Texas region, which often result in flood water depths in public rights-of-way exceeding desired levels, the need has been identified for an increased level-of-service in our constructed infrastructure which results in the reduction of extreme storm event flood levels. The application of this simplified method of the consideration of overland flow in public and private improvement projects is intended to maintain water surface elevations (WSELs) from the 100-year storm event at or below the natural ground elevations at the right-of-way (ROW) lines of our depressed, curb and gutter, public streets and thoroughfares. Open channels and roadside ditches are not specifically covered in this paper; yet, the theoretical application is similar.

Where applicable, more complex methods (i.e. unsteady and fully dynamic simulations) may be employed resulting in a more refined storm water infrastructure design; however, the methods presented herein yield acceptable results of controlling overland WSELs within our ROWs without the onerous computational procedures that are often associated with other more dynamic methods.

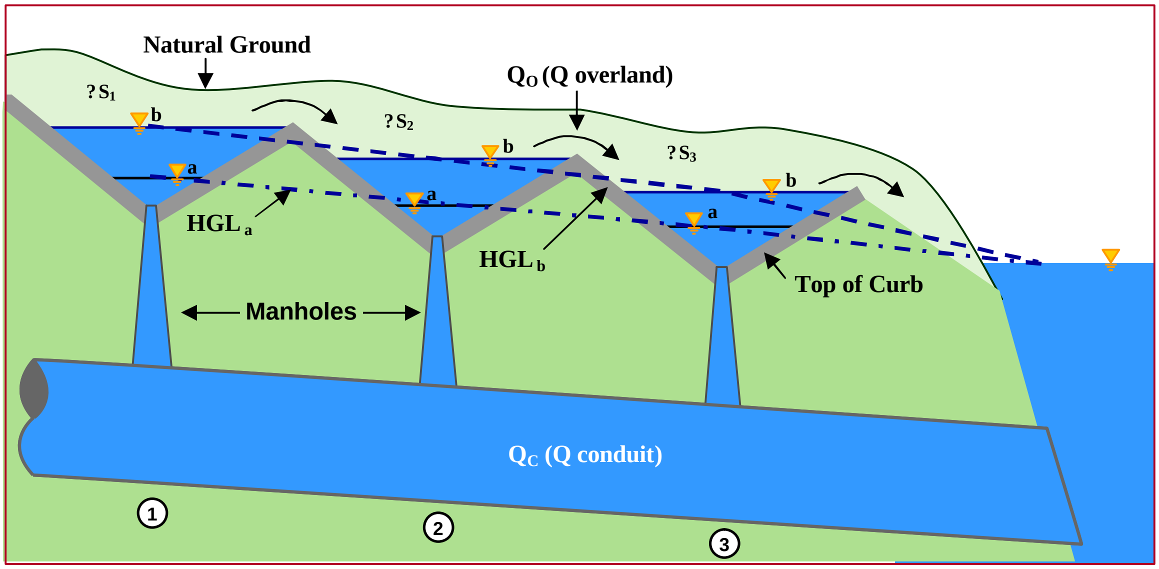
One of the fundamental assumptions correlated with this simplified approach discussed herein is that the determination and mitigation of hydraulic impacts resulting from the project at hand has already been addressed in some fashion. This is most commonly the case where detention basins are employed in a local, sub-regional, or regional basis. In the cases of applied detention basins, the basin outlet, restrictor, and storm sewer reach to the ultimate outfall, if utilized, remains unchanged in terms of design as currently dictated by Chapter 9 of the City Design Manual.

Throughout this document, storm events are commonly referred to in terms of frequency of return. For example, a 2-year storm is an event that has a 50% probability of occurrence in any given year and a 100-year storm is an event that has a 1% probability of occurrence in any given year.

2.0 The Relationship of Overland and Conduit Flow

Overland flow is termed as flow resulting from a rainfall event that is routed along the surface street or other such surface channel in a defined manner. This differs from sheet flow which is a shallow mass of runoff on a sloping surface that commonly does not have a precisely defined bounding condition. Conduit flow is simply that portion of the total system flow routed through the storm sewer system pipe, box, or other closed hydraulic conveyance link.

Figure 1 depicts the typical relationship of overland to conduit flow whereby rainfall is accumulated within a street system and is conveyed to inlets and then ultimately a storm sewer. Once the rainfall intensity or inflow exceeds the capacity of the storm sewer system (inlets, leads, and trunk system), the excess is stored within the street and then, based upon the roadway profile geometry, is eventually routed downhill, typically toward an outfall location. Water balance is maintained by the inclusion of the relationship of storage relative to time.



$$Q_{O\ in} + Q_{C\ in} + \text{Rainfall} = Q_{O\ out} + Q_{C\ out} + \frac{?\,S_T}{\Delta t}$$

Figure 1 - Overland and Conduit Flow Relationship

The actual behavior of a street, inlet, inlet lead, and storm sewer system, when considering the effects of storage, can be somewhat complex. This is especially compounded when the effects of high tailwater at the outfall or outlet are considered. If the outlet WSEL remains unchanged, the increase in pressure head identified by the hydraulic grade line (HGL), say from *a* to *b* in Figure 1, will result in an increase in flow through the conduit. If all conduit conditions remain unchanged (i.e. size, length, and coefficient of friction), the flow in the conduit is directly proportional to the square root of the head loss as applied in Manning's equation. This strong relationship between the increase in driving head on a given conduit system and the resulting conduit flow is a fundamental aspect of controlling WSELs within streets and thoroughfares. Obviously, if high tailwater conditions at the outlet of a system prevent any significant head differential in any given reach of conduit, then the overland flow component of the total system flow (overland plus conduit flow) in conjunction with the effects of storage in the street section relative to time becomes critical.

The WSEL, or flood level, in a depressed roadway section observed during an extreme storm event is not the same level of the pressure head on the storm sewer system as identified by the HGL as the effects of inlets, leads, and manholes are not commonly considered in the HGL computation. When the HGL of a given storm sewer for a particular event is below the gutter line of a roadway section, then the observed WSEL in the roadway is controlled by inlet and lead capacity and roadway geometry. The true effects of inlets, leads, and manholes can be very noticeable depending on the individual storm sewer system and the storm event applied. There is a relationship, however, between the observed WSEL in a depressed roadway section and the HGL of the storm sewer serving the roadway during an extreme storm event when the HGL is above the gutter line. Given that sufficient inlet capacity exists and the inlet leads are sized accordingly, the HGL of the storm sewer system will yield a simplified approximation of the anticipated WSEL in a roadway section, as long as bounding conditions of the HGL exist. As such, in this Technical Paper, the observed WSEL in a depressed roadway section during a 100-year storm event is used interchangeably with the resulting 100-year HGL of the storm sewer as long as the said bounding conditions are recognized as discussed later. This is indeed a significant simplification as applied herein that the designer should recognize. This is also the root concept as applied for controlling 100-year WSELs in depressed roadway sections.

Figure 2a represents a typical series of inflow and outflow hydrographs for a given depressed roadway section. The inflow hydrograph is representative of total system inflow at a given location from upstream overland flow, conduit flow, and rainfall. The system outflow is a function of conduit and downstream overland flow. By combining these two outflow hydrographs, in relation to time, the area under the inflow hydrograph and above the combined outflow hydrograph would therefore represent the storage within the roadway section that would be utilized and later routed through the conduit as depicted in Figure 2b. This is inherently a simplified representation as in many, if not most, conditions in the Houston area, conduit flow will vary greatly based upon outlet tailwater conditions relative to time. As described above, the conduit flow may be reduced to zero or even become negative flow – representing flow from the outlet *upstream* into the conduit – and overland flow in conjunction with storage will become the predominate drainage mechanism.

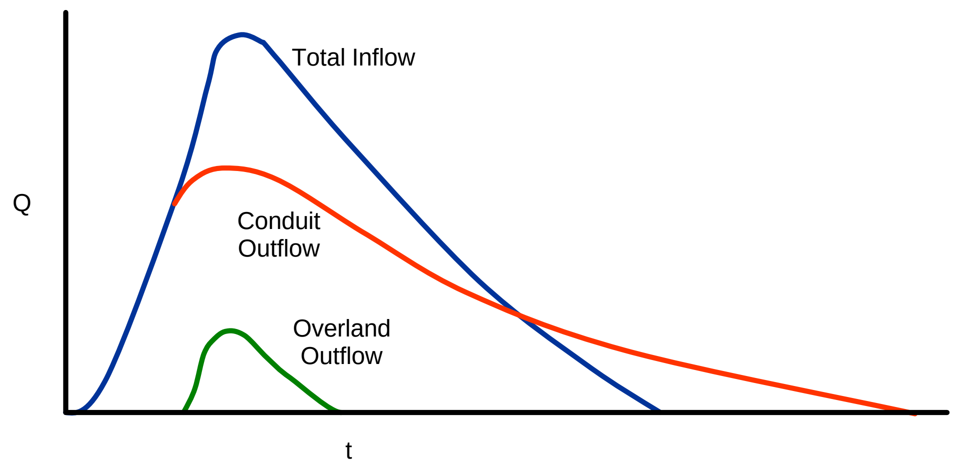


Figure 2a – Inflow and Outflow Hydrographs

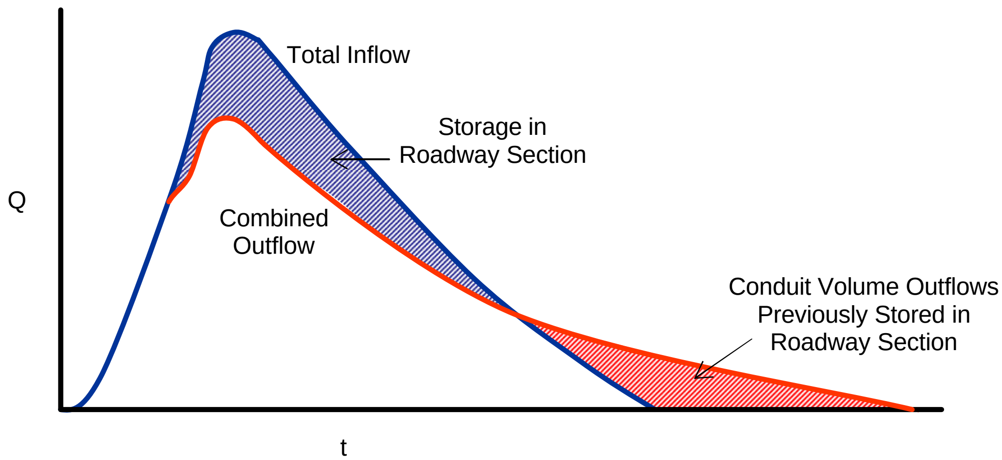


Figure 2b - Combined Outflow Hydrographs Showing Storage

3.0 Storage and Routing Considerations

The effects of storage and routing cannot be over emphasized in the computational process of urban storm water management. As the pressure head on a given storm sewer system is increased as visualized by the HGL, the resulting WSEL will reach a level within a given depressed roadway section whereby flooding beyond the ROW will occur. While the HGL can be calculated based upon Manning's equation to represent an ever increasing pressure head, it is not realistic to have the HGL exist above established boundary conditions such as adjoining natural ground elevations. Once the HGL reaches such known boundary conditions in terms of elevation, then the pressure head will cease to rise, or rise only minimally, as areal flooding will occur beyond the known or established bounding natural ground elevations.

As the WSEL rises within a given roadway section, the head on the storm sewer increases thereby increasing the flow within the storm sewer system (assuming the downstream head level is not increased by the same increment) up to a point at which little, if any, increase in WSEL is possible. This point may be when areal flooding beyond the ROW is experienced, when overland flow occurs within the ROW, when sheet flow occurs away from the system outside of the ROW, or a combination of these phenomena. In all of these cases, the storage within the roadway section plays an important part of the overall water balance equation.

The actual routing of the total system flows, considering inflow, overland flow, conduit flow, and storage relative to time is somewhat cumbersome by hand calculation methods. Computer simulations using dynamic models may be employed[2]; however, this may be determined in many cases to be too onerous for a given projects circumstances. Hand calculation methods can be performed and have been performed successfully in actual test cases whereby an assumed 100-year water surface elevation in the roadway section is used to compute storage, the overland flow within the roadway, and the flow within the conduit. The resulting HGL is then checked against the assumed WSEL in the roadway. After several iterations, convergence is achieved in that the assumed WSEL in the roadway approximately matches the HGL calculations of the storm sewer

[2] U.S. Environmental Protection Agency. *U.S. Environmental Protection Agency's Storm Water Management Model (SWMM)*, Retrieved May 1, 2003 from http://www.epa.gov/ednrmrl/swmm/

system. This type of computation procedure does not consider the effects of inlet, lead, and manhole losses, but is suitable for this type of application and does yield results that have compared favorably to fully dynamic simulations.

4.0 Simplified WSEL Control via HGL Adjustments

A simpler approach to controlling the 100-year WSEL within the ROW can be achieved by manipulating the position of the HGL resulting from the storm sewer head losses calculated in the design process. This method does not consider the effects of storage; however, the fast and easy computational process and the resulting minor increase in size of some storm sewer reaches to achieve the desired results can readily offset the burdensome storage and routing computations that would alternately be required.

The friction loss of a given conduit can be represented by Manning's equation as follows:

$$h_\ell = L\left(\frac{Qn}{1.49\,AR^{2/3}}\right)^2$$

where

h_ℓ = head loss in conduit reach (ft)
L = length of conduit reach (ft)
Q = flow (cfs)
n = Manning's roughness coefficient
A = cross-sectional area (ft^2)
R = A/P, the hydraulic radius (ft)
P = wetted perimeter (ft)

This equation is commonly used to compute the friction loss of a given conduit reach and the resulting upstream HGL ordinate is plotted in a profile view. A series of successive computations for a given storm sewer system results in the HGL plot of the system for a given design event.

As typically applied in Houston, the 2-year frequency design storm event is used to initially size the storm sewer system for a given project and then the 2-year HGL is computed, using the outfall soffit as the starting WSEL[3], to insure its position is at or below the gutter line of the roadways within a given project area. A 100-year storm event, as identified by the intensity-duration-frequency (IDF) curve in the City Design Manual, is then applied to the storm sewer system and a check is made to insure that the 100-year HGL, using the 25-year WSEL at the outlet as the starting WSEL, is at or below the natural ground elevations along the ROW. Should it be evident that the 100-year HGL for a given storm sewer system exceeds natural ground

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[3] In cases where drops exist, the HGL computations begin again at the soffit of the conduit upstream of the drop. Refer to Chapter 9 of the City Design Manual for further explanation.

elevations along the ROW, then the careful examination of the storm sewer system should be performed to identify certain storm sewer reaches that have a relatively high degree of friction head loss. Then these particular reaches can be upsized, usually only by one or two sizes, to yield a reduction of the HGL below the natural ground elevations along the ROW. Building upon the previous discussion within this paper, this simple process assures that given a 100-year storm event, the anticipated resulting WSEL will be contained within the roadway ROW[4].

As has been commonly applied in the past, a 25-year starting water surface elevation should be applied to the 100-year HGL computations. The logic behind this application is simply that when a 100-year event occurs over a project area, the tailwater elevation at the outlet is usually some lesser level other than the 100-year WSEL. The issue of tailwater and the determination of the 25-year WSEL at the outlet are discussed in the next section.

What is important to note is that the storm sewer system is not being *sized* for the 100-year storm. The storm sewer system is indeed still being sized for a 2-year storm and is then simply being stressed with a 100-year storm event to assess the performance of the system. In many cases, no changes to the storm sewer system in terms of conduit sizing are required in order to insure the 100-year HGL remains below the ROW elevations. In other cases, only minor increases in conduit size for some reaches of an overall system are required. In one test case, the storm sewer system, originally designed for a 2-year event, was indeed designed and sized for a 100-year event just to examine the change in conduit size. The resulting storm sewer sizes increased significantly with the outlet pipe increased from a 66-inch storm sewer by 6 pipe sizes to a 102-inch sewer. The methodology described within this paper in no way reflects any increases of this nature based upon several project test cases and it is fundamental to recognize that the *sizing* of the storm sewer systems remain based on a 2-year design event. The 2-year designed system is simply examined for behavior under a 100-year storm event and then slight alterations to the design, if needed at all, are made to maintain the 100-year HGL at or below the natural ground elevations along the ROWs.

5.0 Determination of the 25-year or Other Starting Water Surface Elevation

In project situations where the 100-year WSEL, or less (i.e., 50-year or 10-year), already inundates the project area(s), for whatever reason, it is not the intent of these guidelines to require the design engineer to resolve problem areas beyond their reasonable control. Chapter 9 of the City Design Manual stipulates this criterion and allows the submittal of documentation and an analysis demonstrating this project situation. The intent is to have the design engineer examine the overall system performance (overland and conduit components alike) to insure a desired level-of-service is achieved. In cases where the 25-year WSEL of a nearby bayou, for example, inundates a project area, then obviously lesser tailwater elevations, for analysis purposes, would be warranted. Again, the proper submittal of documentation with supporting analyses is stipulated for these conditions within Chapter 9.

[4] The issue of inlet capacity is not specifically addressed herein, but test cases of typical new development projects using procedures outlined in the FHWA's HEC 22 have shown that the standard inlet design density as called for in Chapter 9 of the City Design Manual provides for a very suitable inlet spacing to accommodate the hydraulic connection required for the 100-year storm event analyses as described within this Technical Paper.

In most commonplace applications, the 100-year WSEL at the outfall is known or established. This outfall condition is usually at a detention basin or channel. In many cases, lesser event WSELs are also known and the 25-year WSEL may be determined by log-linear (or other applicable non-linear methods) interpolation. In cases where actual routing is performed, through a detention basin for example, the determination of the 25-year WSEL is easily determined via interpolation given that bounding design event WSELs are established for the basin.

Lacking suitable and available data from which the 25-year WSEL can be reasonably estimated, a consistent means of establishing the 25-year WSEL at an unspecified outfall location in Harris County was needed. This would allow a designer the ability to rapidly establish the 25-year WSEL without laborious routing or other calculations. To simplify the discussion within this section, Figure 3 illustrates a decision flow chart applicable to typical projects at an unspecified location involving a detention basin used to collect storm water from one or multiple storm sewer systems within a new development or improvement project.

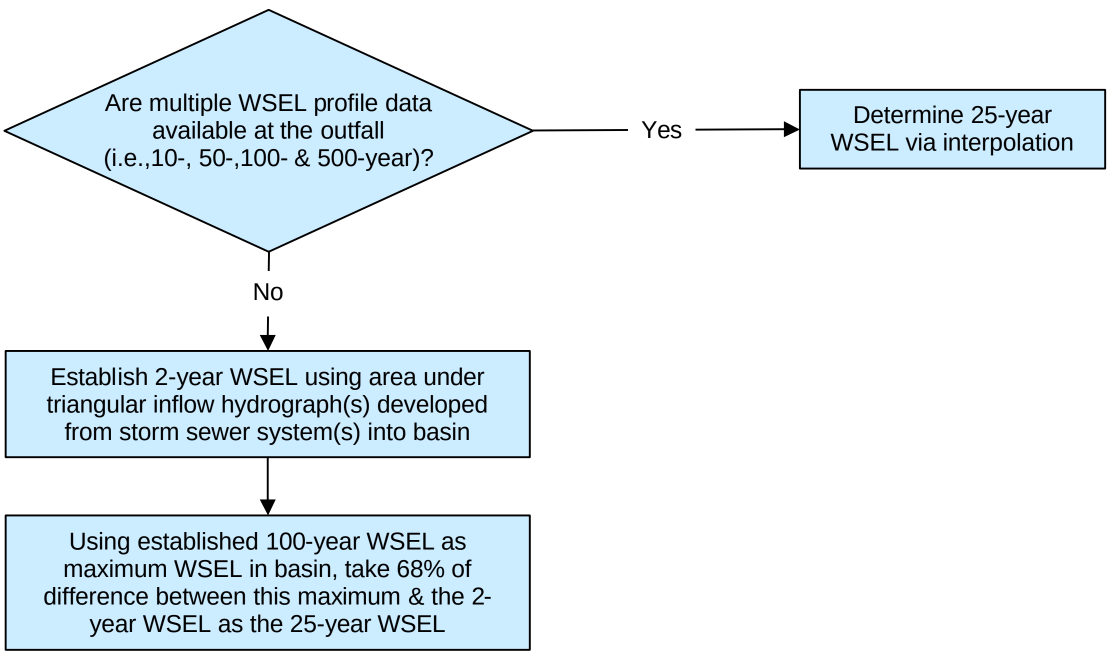

Figure 3 – Decision Flow Chart for Determining the 25-Year WSEL in a Detention Basin

Where detention basins are utilized, the 100-year WSEL in the basin is known or established as a design parameter based upon basin sizing. While other frequency storm event WSELs are unknown without performing storm water routing through the basin, the 2-year discharge and time of concentration at the outfall(s) into the basin from the designed storm sewer system is known. The 2-year WSEL can then be estimated for the basin utilizing the volume under the triangular hydrograph produced in the Rational Method as shown in Figure 4 when calculated using the peak discharge and time of concentration at the outfall(s). Note that if the soffit of the outfall conduit into a basin or channel is used as an estimate of the 2-year WSEL in the basin, as is done for the beginning WSEL in the 2-year HGL calculations for the storm sewer system, this may often prove to be very conservative. This volumetric method of determining the 2-year WSEL in a detention basin as described above does not consider any outflow from the basin in a 2-year event; yet, further refinement can be made by including a calculated discharge from the basin and reducing the peak of the inflow hydrograph accordingly. The resulting volume under the hydrograph could be used to establish a more accurate 2-year WSEL in the basin. In essence, a design engineer may consider the effects of basin outflow and therefore reduce the volume and resultant WSEL computed for the 2-year event. From test cases, the reduction of the inflow hydrograph, thus considering outflow from the basin, produced only minor reductions in the 2-year WSEL.

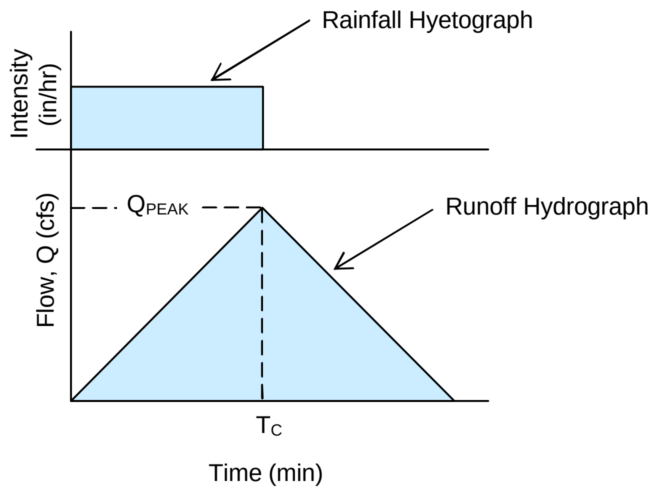

Figure 4 - Rational Method Rainfall Hyetograph & Runoff Hydrograph

In order to better understand the *typical* relationship between the 2 and 100-year WSELs throughout Harris County, several bayous and creeks were examined based upon level-of-service analyses previously performed on these channels[5]. In these previous studies, WSELs for various storm events were determined in the channels and by taking the flows used in the hydraulic models (HEC-RAS) for the various events, a 25-year flow was interpolated and then the models recomputed to determine the 25-year WSELs. From these test runs of numerous channels throughout Harris County, it was determined that the 25-year WSEL exists at approximately a 68% level between the 2 and 100-year WSELs. In other words, taking 68% of the difference between the 2 and 100-year WSELs will yield a reasonable approximation of the 25-year WSEL.

Likewise, if only the 10 and the 100-year WSEL are known at a particular location, a quick and reasonable estimate of the 25-year WSEL can be made by taking 38% of the difference between the 10 and 100-year WSELs. This percentage was determined using the same methodology as described above as supported by previous studies. If suitable information exists at a locale yielding many storm event frequency WSELs (i.e. 10, 50, 100, and 500-year WSELs), then direct interpolation of the 25-year WSEL is most suitable.

[5] These level-of-service analyses were previously performed in support of the Harris County Watershed Master Plan, Harris County Flood Control District (HCFCD), 2004.

As with the 2-year HGL computation, drops in storm sewers can prove problematic as partial flow in the conduits may exist towards the outfall. This same situation applies if the 25-year WSEL determined for a project location is below the soffit of the outfall conduit. In these cases, the soffit of the outfall conduit should be used as the starting WSEL for the 100-year HGL computation similarly as with the 2-year HGL computation. The upstream conduit soffit at the drop should be used as the starting WSEL for upstream HGL computations if the HGL at the drop location is below the said conduit soffit. This typically eliminates the computation of partial flow within any conduits.

In any case, the position of the 25-year WSEL will have a direct correlation to the adjustment, if needed, of the 2-year storm sewer design as described in previous sections. There are many applicable methods of determining the 25-year WSEL at a given outfall location. Where routing procedures are not commonly performed, the method described in this section will prove suitable in most applications. Should situations dictate the utilization of a lesser event starting WSEL for the examination of the position of the 100-year HGL within a given project as described at the beginning of this section, due documentation as outlined in the City Design Manual is suitable in support of the design engineer's judgment in these regards.

6.0 Overland Flow Paths and the Integration of the Position of the HGL

Despite the best design employed for a given storm sewer system, in typical situations, a given extreme storm event will render the storm sewer ineffective due to high tail water conditions. As such, the proper consideration of the overland flow path to the project outfall or outlet is critical in terms of flood protection to the project area. In essence, this is primarily insured by the design of the roadway profile of a given project in a cascading manner to the project storm sewer outfall or outlet. In some cases, the storm sewer may not track readily with the overland flow path(s) which is not necessarily a negative as long as the proper consideration of overland flow in relation to conduit flow is understood and the design accommodates this condition. While the roadway serves as the primary overland flow mechanism, it is also critical to consider the means by which overland flow will be routed from the roadway to an outlet such as a detention basin within a storm sewer easement or other such allocated pathway. Conveyance links (i.e. large swales, ditches, etc.) are needed to provide a suitable pathway for anticipated floodwaters to the outlet. Caution should be used in new developments where houses, buildings, fences, and other structures would block or impede these floodwaters from proceeding along their intended pathway.

Another overland flow consideration that must be addressed is the flow from a localized outfall or outlet such as a detention basin to an ultimate outfall at the watershed level. In other words, the designer must consider the scenario of overland flow in terms of leaving the project area via a spillway, within a roadway section, or another travel pathway towards the ultimate receiving channel(s) within the watershed. This should be documented in the design via flow arrows on the drainage area map or by other means. The purpose is to demonstrate the overland flow pathway(s) given the condition that the storm sewer system in conjunction with the detention basin, if applicable, for a project area have been completely inundated and rendered incapacitated in terms of facilitating additional inflow.

Given that the 100-year WSEL in a given roadway section is maintained within the ROW via manipulation of the HGL as previously described[6], the roadway profile itself must be designed in such a fashion to provide a reasonable surface pathway to the project outfall or outlet. Once completed, an easy check can be made of the resulting hydraulic profile, as required in Chapter 9 of the City Design Manual. Figure 5 illustrates a hydraulic profile of an example project where the storm sewer as designed for the 2-year event maintains the 100-year HGL below natural ground elevations at the ROW using the 25-year starting WSEL determined as described above. In this case, no adjustment to any conduit sizing was required. What is problematic, however, is the roadway profile relative to the detention basin (labeled *Pond*). This basin is intended to be the receiving outlet for overland flow; yet, the roadway profile does not adequately accommodate this. Also, not visible in the profile plot, the dedicated storm sewer easement containing the last short reach of storm sewer into the basin is not designed to accommodate the incoming overland flow at this location.

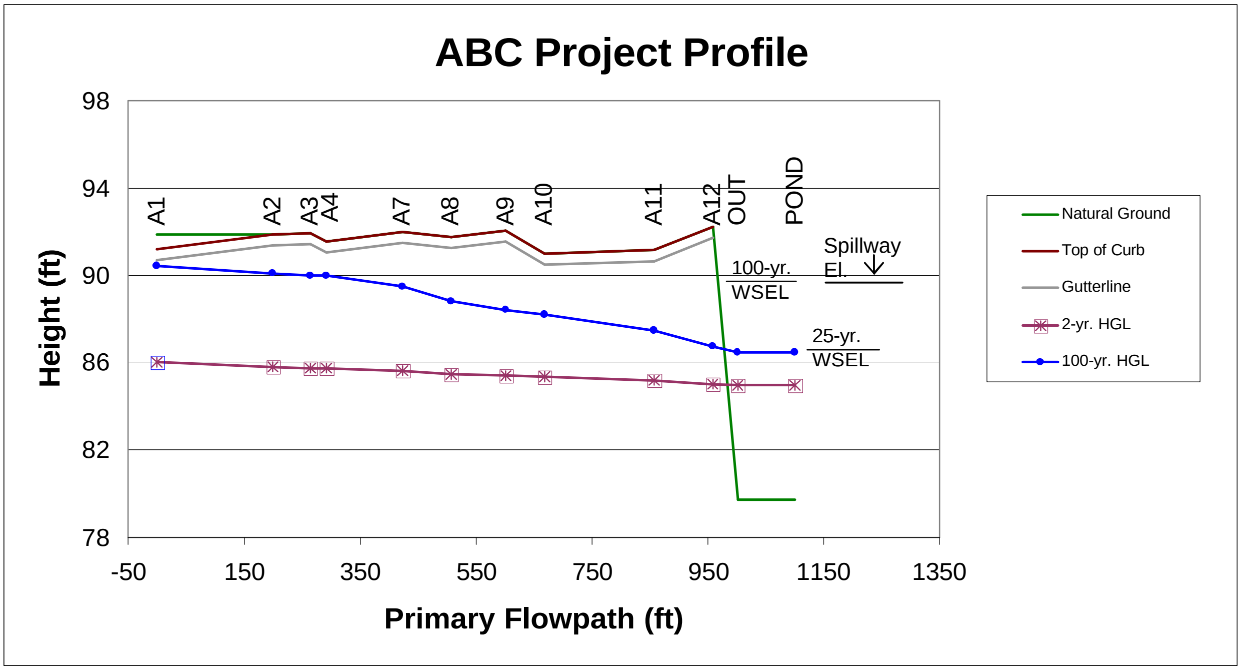

Figure 5 – Example ABC Project Hydraulic Profile

[6] The HGL does not correlate exactly with the observed WSEL in a roadway section during an extreme storm event as the effects of inlet, lead, and manhole losses must be accounted for. Studies have shown that these losses vary depending upon the ability of the storm sewer to receive additional inflow. The HGL position, as applied herein, is only an approximation of the actual WSEL that would be observed in a roadway section during such an extreme event.

Figure 6 illustrates another example project hydraulic profile. In this case, the 2-year design HGL is suitable in terms of its position relative to the gutter line as required in the City Design Manual, but the 100-year HGL was above natural ground through much of the project area (labeled as *100-year HGL*) indicating overland flow in conjunction with storage will certainly be an integral part of the overall drainage system given a 100-year storm event. In this case, in lieu of computing the effects of storage and the routing of these overland flows, a few reaches of storm sewer where high levels of head loss were evident were increased one size only. The result is viewed in the HGL plot labeled *100-year Altered*. This proved to be an easily applied economical solution which provided the increased level-of-service desired. As with the previous example, notice the problematic design with respect to the overland flow path to the basin or *Pond* which is indicated as the receiving outlet for overland flow.

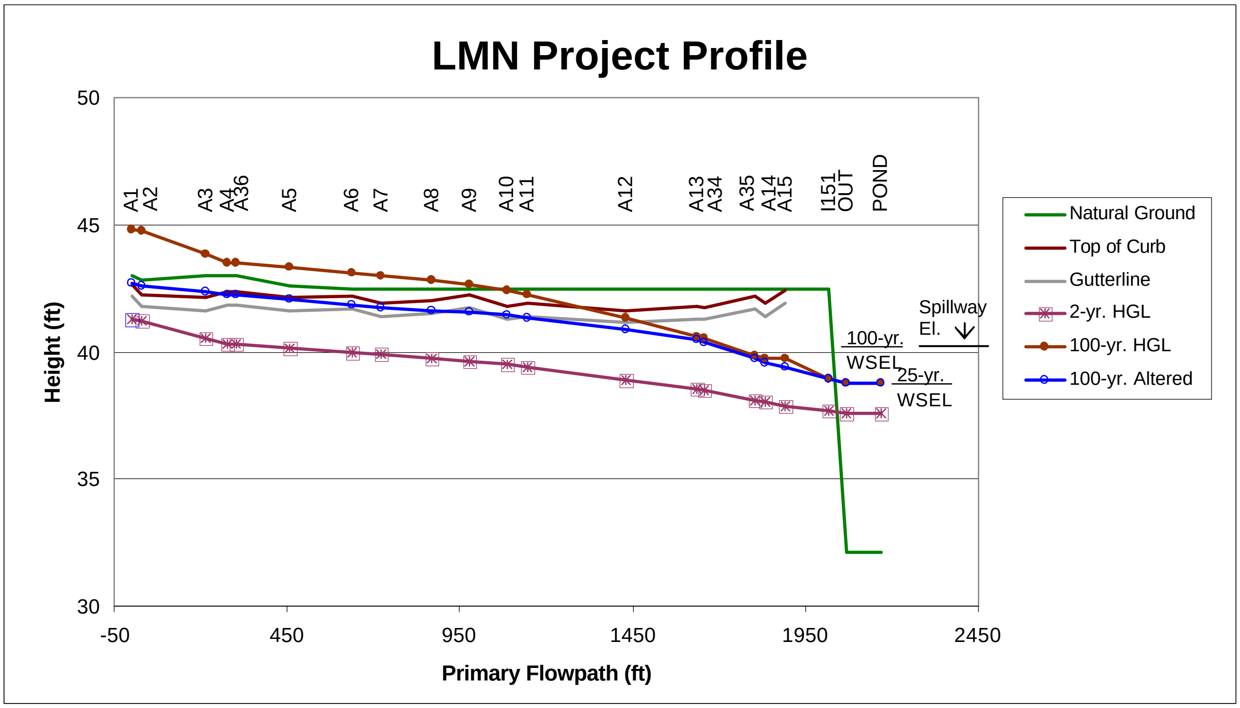

Figure 6 – Example LMN Project Hydraulic Profile

Lastly, Figure 7 illustrates an example project hydraulic profile where the 2-year design facilitated the position of the 100-year HGL relative to the natural ground elevations within the project area. Notice the evident drop in the storm sewer near the outlet as viewed by the sudden drop in the 2-year HGL. Also notice that the 25-year starting WSEL for the 100-year HGL plot was slightly above the soffit of the upstream conduit at the drop as indicated by an ever slightly higher position of the 100-year HGL at the drop. Had the 25-year starting WSEL been below this elevation, it would have been necessary to raise the said 25-year WSEL to match the upstream conduit soffit at the drop. While not clearly visible, this roadway profile suitably accommodates the overland flow pathway to the designated overland flow outlet, again in this case the detention basin or *Pond*.

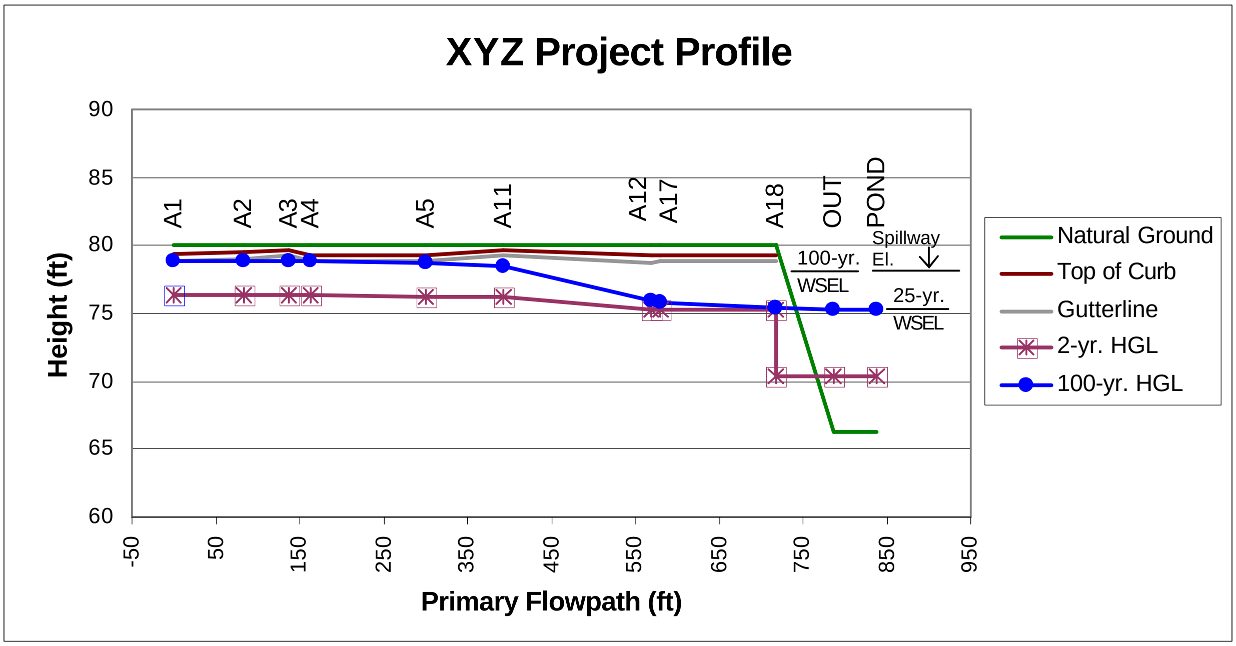

Figure 7 – Example XYZ Project Hydraulic Profile

7.0 Simplified Design Process Flowchart

Figure 8 is a simplified design process flowchart depicting an overview of the process discussed herein. Again, there are many variations of this application and simplifications of the actual performance of the system are assumed. This is primarily true in cases of inlet, lead, and manhole behavior as applied to the overall system performance.

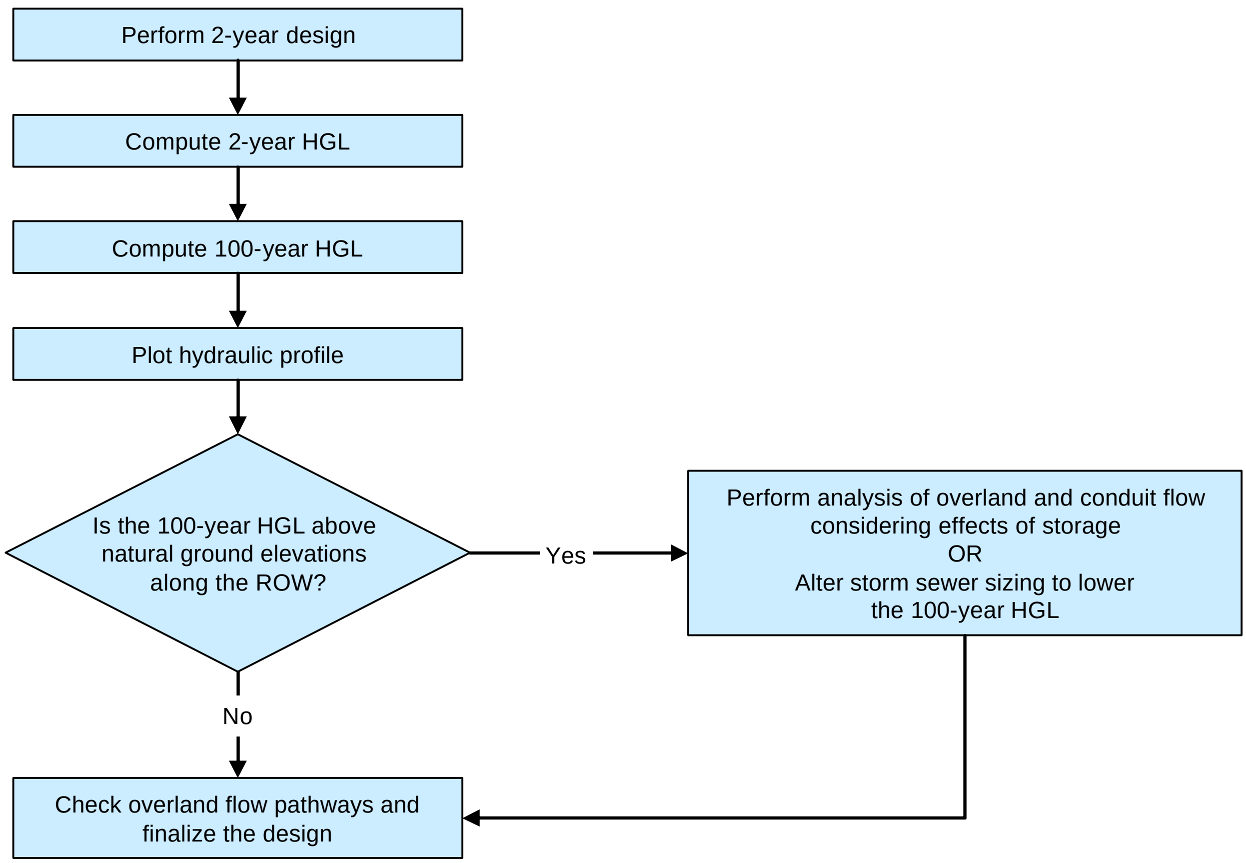

Figure 8 – Simplified Design Process Flow Chart

8.0 Summary

Given the repetitive nature of severe storm events and the associated flooding which commonly occurs in the Houston region, it is desired to have an increased level-of-service in terms of flood level reduction. To achieve this, several changes to Chapter 9 of the City of Houston Design Manual have been initiated. One specific criterion requires maintaining the 100-year HGL for a new storm sewer system to be at or below the natural ground elevations along the roadway ROWs where reasonably possible. There are many ways of achieving this desired result. One manner involves the computation of the routing and storage of overland flows to demonstrate maintaining the 100-year WSELs within a project area within the ROW. This is somewhat arduous if done via hand calculations but is certainly achievable. Computer models simulating the actual dynamic behavior of the system may also be employed if deemed warranted.

Another method considering the 100-year storm event, as presented herein, involves the simple manipulation of the 2-year storm sewer design, if needed at all, to reduce the head loss identified in certain reaches of the storm sewer system such that the resulting pressure head represented by the 100-year HGL is lowered to a desired level. Based upon several test case studies, this methodology provides an easily applied solution to the design requirement without significantly affecting, if at all, the initial storm sewer sizing.

In all cases, overland flow pathways are critical to the performance of the entire storm sewer system and the behavior of the overland flow pathways to the receiving outfall or outlet must be carefully scrutinized in terms of anticipated performance.